CRD Report

Earthquake Resiliency Implications of CRD EV Adoption

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Executive Summary

The adoption of electric vehicles (EVs) has many benefits, such as reduced emissions, better performance, and economic savings on maintenance and fueling. The Capital Regional District (CRD) of Victoria has one of the largest concentrations of EVs in British Columbia (BC), and this concentration is only expected to grow with time. The CRD is also located in a portion of BC with a high seismic hazard and would be profoundly affected by a Cascadia Subduction Zone (CSZ) earthquake. Until recently, maintaining vehicle use after an earthquake has depended on the resilience of the fuel infrastructure, but the increasing use of EVs will transfer some of that dependence to the resilience of the electrical system.

Analyzing past earthquakes in Chile, Japan, and New Zealand provides some insight into how to increase earthquake resilience. The 2010 Chile earthquake showed the importance of available excess generation capacity, private forms of communications, and utilizing small generators for recovery in isolated areas. The 2011 Japan earthquake illustrated the value of not locating too much generation capacity in tsunami zones, utilizing rolling blackouts for recovery, and the exceptional performance of microgrids. The 2011 New Zealand earthquake taught the danger of buried cables in liquefaction zones and how impactful spending money on resilience upgrades can be.

BC Hydro can improve the resilience of the electrical grid by adding generation capacity, relocating grid elements from tsunami and liquefaction zones, planning to have resources for repairs available, and establishing aid agreements with surrounding areas. VI can improve its fuel resilience by retrofitting ports, increasing fuel storage, and planning for how fuel will be prioritized after an earthquake.

The CRD can improve their organizational earthquake resilience by establishing a local microgrid and utilizing the battery capacity of their EV fleet to provide mobile storage following an earthquake. The CRD can also plan for what their expected vehicle and generator fuel needs would be after an earthquake and establish sufficient storage.

EVs can be used after an earthquake to establish a communication network by acting as nodes in a mobile network, and a 180 s simulation showed that a Nissan Leaf Plus would only use 0.018% of its battery capacity to provide this function for that time. In a 24 hour period, a Nissan Leaf Plus was found to able to donate 400 kWh of energy to a local shelter, assuming the vehicle had access to a fast charger and a microgrid with a 100 kW solar array. Given the Leaf's 363 km single charge range, the same microgrid was able to provide power for 8 Leafs to deliver supplies and people for a 24 hour period.

Introduction

Motivation

The adoption of electric vehicles (EVs) offers a host of benefits compared to internal combustion engine (ICE) vehicles, such as reduced greenhouse gas (GHG) emissions, better performance, and economic savings over the vehicle lifetime [1]. EVs also offer the emergent ability to transfer power from EV batteries to the grid or a building which allows better integration of renewable energy, controlled charging, and the ability to use EVs as mobile energy storage [1] [2].

EVs have seen rapid growth during the last decade, and, even during the pandemic, worldwide EV registrations increased by 41% in 2020 [3]. The resilience of EV sales to the pandemic can be attributed to many countries strengthening emissions standards and ZEV sales mandates, along with the expanding number of available EVs and falling battery costs [3]. By 2040, EVs could represent 12 – 28% of the global fleet, depending on factors such as battery cost reduction and the amount of government subsidies [4].

EV Adoption in the Capital Regional District (CRD)

The British Columbia Hydro and Power Authority (BC Hydro) is the main electricity distributor in the province of BC and generates 43,000 GWh of electricity annually to supply more than 1.9 million residential, commercial, and industrial customers [5]. Close to 95% of BC's electricity comes from renewable sources (hydro, wind, biomass), and about 90% of the province's installed generating capacity is renewable energy [6]. This means that operating and charging an EV in BC has very little associated GHG emissions, and EV fleet adoption has huge potential to reduce GHG emissions for organizations such as the CRD.

Compared to other provinces, BC has been ahead of the curve for EV adoption, and 2020 saw BC with the highest uptake of zero emissions vehicles (ZEVs) in North America, with ZEV sales averaging 9.4% of new vehicle sales for the year [7]. The greatest adoption of EVs in BC continues to be in major urban centers where public charging is more readily available. In particular, the largest concentrations of EVs in BC can be found in the Metro Vancouver area and the Capital Regional District (CRD) on Vancouver Island [8]. With the passing of the Zero Emissions Vehicles Act, mandating 100% of light-duty vehicle sales to be ZEVs by 2040, adoption of ZEVs is almost certain to continue increasing in these regions.

Vehicle Disaster Relief Functions and Propulsion System Resiliency

Vehicles play crucial roles during the early stages of disaster recovery. In the hours or days following a disaster, vehicles are needed for search and rescue efforts and provide assistance by transporting people in medical need, along with critical supplies, such as food, water, and medicine. In medium to long term recovery, vehicles resume their pre-disaster functions as permanent physical and social structures begin to be restored [9].

Until recently, maintaining vehicle propulsion after a disaster relied on the resilience of the fuel infrastructure, and vehicles would only be able to provide disaster relief for as long as fuel supplies lasted.

Natural disasters can impact the fuel infrastructure in a multitude of ways. Loss of power can lead to refineries being unable to operate and pumping stations not able to move oil and gas through pipelines. Pipelines themselves can be damaged by high winds, flooding, and earthquake induced stresses. Additionally, natural disasters can impact fuel supply by blocking or destroying transportation networks such as roadways, bridges, and ports [10].

While the fuel infrastructure will remain critical for the foreseeable future, increased adoption of EVs will mean that maintaining vehicle propulsion after a disaster will start to depend more heavily on the resilience of the electrical system.

Focus of the Report

As shown in figure 1, the CRD coincides with the portion of BC that has a high level of seismic hazard and would be most affected by a great Cascadia Subduction Zone (CSZ) earthquake. As this type of earthquake is considered a worst-case natural disaster for the region, it will be the focus of this report. To study the impacts of this scale of earthquake on the power system, past earthquakes in Chile, Japan, and New Zealand will be examined. Lessons from these earthquakes will be compiled and applied to how the CRD can increase earthquake resiliency and maintain the use of EVs in the disaster aftermath. These suggestions will be compared with how fuel resiliency might be improved in the region.

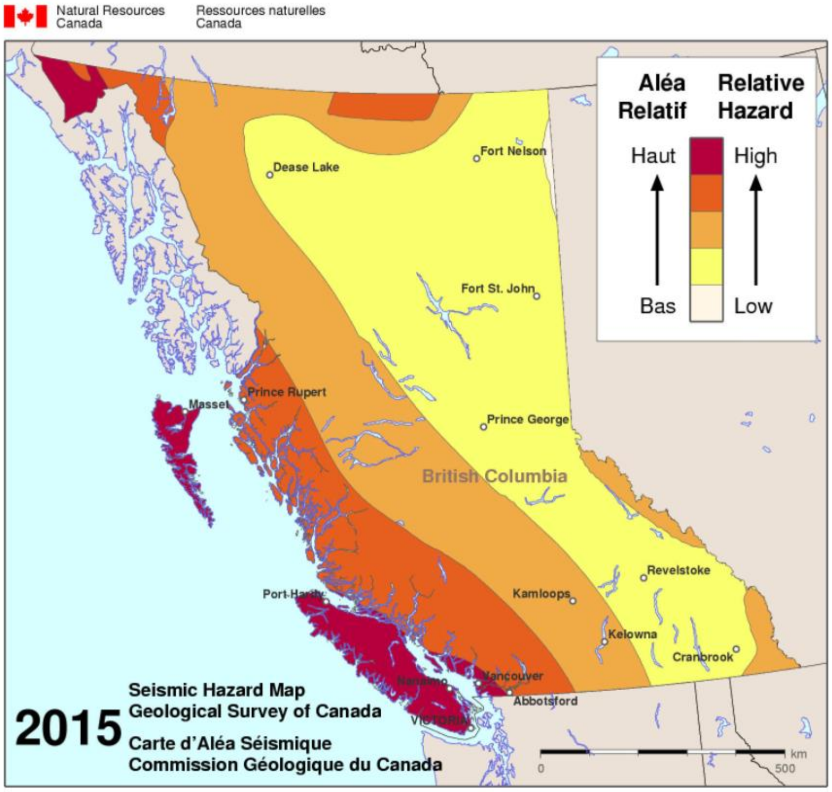
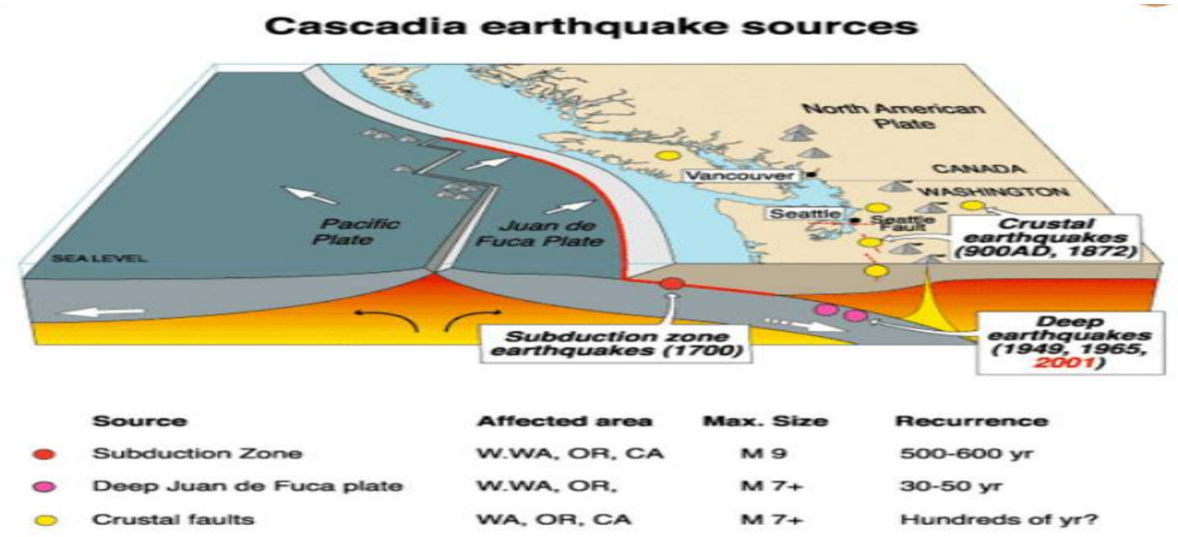


Figure 1 - British Columbia Seismic Hazard Map [11]

Cascadia Earthquake Background

The CSZ is a region extending from northern California to central Vancouver Island (VI), where the Juan De Fuca, Explorer, and Gorda plates are driven beneath the North American plate in a subduction process [12]. Shown in figure 2, VI is located where the eastward moving Juan De Fuca plate is sliding beneath the western portion of the North American plate. The subduction zone is locked and slowly accumulating strain. When the strain is released, a massive “megathrust” earthquake is produced. This type of great subduction zone earthquake is the largest in the world and the only type capable of earthquake magnitudes in excess of 8.5 M [13]. Geologic evidence from buried soils, tsunami deposits, and liquefaction features have provided the understanding that many great earthquakes have occurred in this region over the last several thousand years, with the most recent being a 9.5 M earthquake in 1700 AD [14]. Estimates of the probability of another earthquake of this magnitude occurring over the next 50 years range from 7-15% for an earthquake that affects the entire Pacific Northwest to about 37% for an earthquake that affects southern Oregon and northern California [12] [13].



	Source	Affected area	Max. Size	Recurrence
●	Subduction Zone	W.WA, OR, CA	M 9	500-600 yr
●	Deep Juan de Fuca plate	W.WA, OR,	M 7+	30-50 yr
●	Crustal faults	WA, OR, CA	M 7+	Hundreds of yr?

Figure 2 - Cascadia Subduction Zone and Earthquake Sources [15]

Earthquakes mainly cause damage through ground shaking and secondary effects, such as liquefaction, landslides, and tsunamis. Liquefaction is a phenomenon where an earthquake increases pore-water pressure in sediment and reduces grain-to-grain contact forces. The sediment then loses strength and behaves as a fluid [14]. Large earthquakes can also cause damage through aftershocks which can bring down already weakened structures. Following the 2010 earthquake in Chile, 19 aftershocks larger than 6.0 M were experienced in the first month [12].

The economic impacts of a Cascadia earthquake would be staggering, with losses estimated at upwards of $70 billion USD for Washington, Oregon, and California [12]. Much of the infrastructure in the region was constructed before it was understood that this area could experience subduction zone earthquakes. Roads and bridges are likely to see damage from shaking and landslides. Coastal ports could see damage from tsunami, severe currents, and liquefaction. Underwater landslides and debris could lead to the closure of shipping channels. Water systems could take from weeks to months to restore functionality and could take several years for complete restoration. Power outages could only be a matter of days in inland areas but could range from weeks to months in coastal regions. Communication networks may see damage or be overwhelmed in the immediate aftermath [12]. Many critical infrastructure systems are also interdependent. Damaged transport routes may impair crews from repairing downed power lines, and extended blackouts can lead to the failure of communication systems, water treatment plants, and hospitals [16]. Figure 3 shows an example of the possible connections between critical infrastructures.

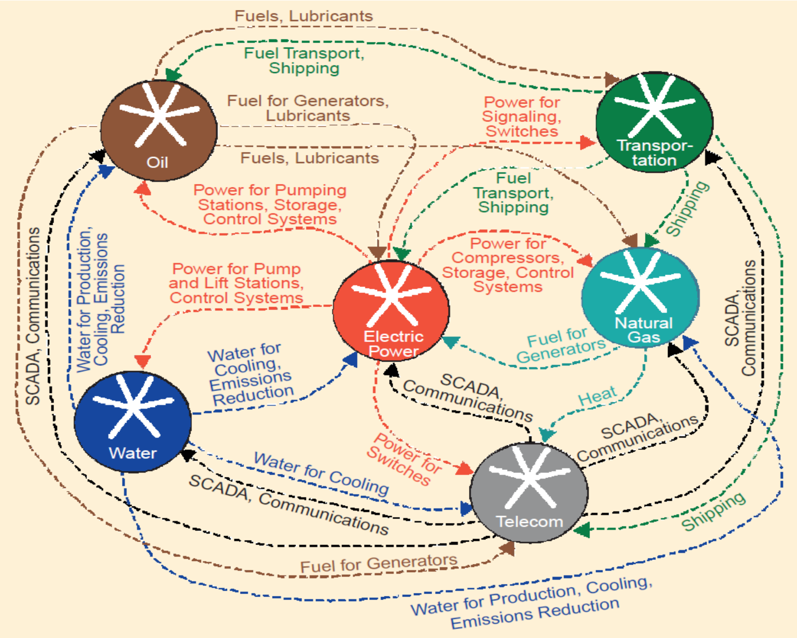


Figure 3 - Network of Dependencies between Critical Infrastructures [16]

Past Earthquake Impacts on the Power System

Chile 2010 Earthquake

On Saturday, February 27th, 2010, an 8.8 M earthquake struck the central region of Chile, affecting over 8 million people [17]. 521 people were killed, and the economic impact was valued at $30 billion US dollars [18]. The epicenter of the quake was located where the Nazca plate subducts beneath the South American plate. It resulted in a rupture 500 km long by 100 km wide and produced a tsunami that damaged 500 km of coastline. Highways, railroads, ports, and airports all saw damage due to ground shaking and liquefaction [17]. The earthquake caused a blackout that affected 4.5 million people and took days in some areas, and weeks in others, to recover the full supply [18].

The Chilean Central Interconnected System (SIC) provides power to over 93% of the population. Following the earthquake, a blackout took place for a load of 4522 MW. 693 MW of the existing generation plants were affected and removed from service for repairs, while 950 MW of plants that were still being built were put on hold to conduct assessment [19]. In previous years, Chile had seen growing investment in power plants, so the missing plants did risk the general supply of energy [18].

Generation equipment is generally built to high standards which contributed to its good performance during the quake. Figure 4 illustrates the impact the earthquake had on the various sources of energy generation.

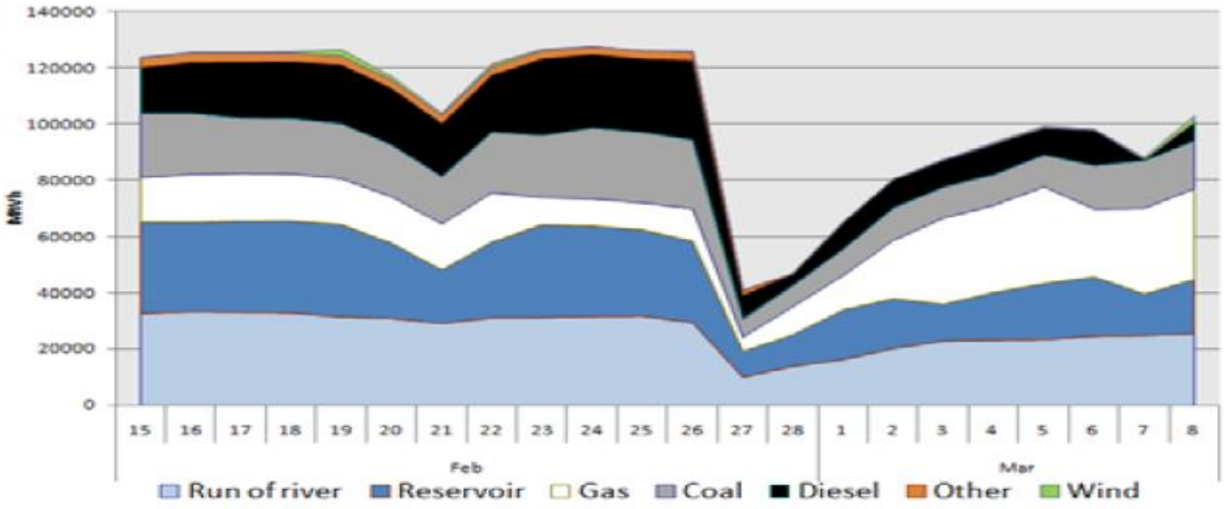


Figure 4 - Chilean Energy Generation Mix Before and After Earthquake [19]

Chile’s transmission network has limited route dispersion and redundancy since it follows the long and narrow layout of the country [17]. The electrical grid in Chile is designed using the N-1 security criteria which allows system operation to continue normally in front of any line circuit or generation outage, without cascading failure. After the earthquake, the central part of the country was separated from the south and a two-island scheme was used for operation [19]. The transmission network was able to provide power within 24 hours and the islands were connected within two days. The fast recovery of the transmission service was attributed to quality infrastructure construction and the fast and competent response of the repair staff.

While restoring supply at the generation and transmission levels was quick, restoring the supply to the end consumer was a longer process. Several parts of the distribution network were severely damaged, and there were coastal regions where the distribution network was completely destroyed by falling houses or washed away by the tsunami [19]. The 220 kV system had been designed to appropriate seismic standards and performed well. In coastal regions, the lower voltage subtransmission system suffered sporadic damage from high levels of shaking. After two weeks, distribution system service was brought back online [17].

Commercial power outages and loss of reserve power in distributed network facilities lead to telecommunication being overwhelmed [17]. Problems with the communication network lead to difficulty assessing the damage and safety of the distribution network and reporting points of failure between low level voltages lines and buildings [17] [19]. Private communication systems remained functional as they used repeaters that fed through still operational low voltages lines, batteries, and photovoltaic (PV) panels. While these networks collapsed when the batteries had lost their capacity, they still offered enough use to facilitate the initial energy restoration activities [18].

The distribution companies did not have the resources available for the huge number of repairs and relied heavily on imported human and technical resources from other parts of the country and subsidiaries in neighbouring countries [18]. Since distribution equipment generally failed due to collapsing walls, landslides, and tsunamis, and not due to design, it didn't seem necessary for Chile to increase future design specifications. Rather, investigators in the incident have encouraged Chile to use a decentralized, local focus on distribution dispatch, during system recovery, to improve operation reaction speed and adapt to local realities [18]. Mobile generators in the 100 to 250 kW range were found to be most effective in supporting recovery in isolated areas and tsunami affected towns. Units in the 1 to 10 kW range were helpful in supplying electricity to critical loads such as hospitals, firehalls, gas stations, and communication antennas. Unfortunately, fuel supplies were extremely limited due to the behaviour of the population, damaged roads, and fallen bridges. Emergency trucks were still able to be refueled by using the army's strategic fuel reserves [18].

Japan 2011 Earthquake

On March 11th, 2011, a large earthquake occurred off the coast of Tohoku, Japan. The earthquake was 9.0 M, caused intense shaking for 120 – 190 s, and triggered a tsunami that reached heights of 9.3 m along the coastline of the Fukushima prefecture [20]. The earthquake resulted 15,984 confirmed deaths, with more than 2,000 people unaccounted for, and caused an estimated $15 billion (US) worth of damage [21]. Most of the earthquake damage was in the Tohuku region, served by the Tohuko Electric Power Company (ToPo), and the northern part of the Kanto region, served by the Tokyo Electric Power Company (TEPCO). The earthquake interrupted electricity for 8.7 million customers [20]. After two days, 1.5 million were still without power, and after three days, 300,000 remained without electricity [21].

14,000 MW of generation plants were impacted, mainly by the tsunami and some shaking damage [22]. Significant damage was caused to thermal power stations. Three thermal stations (generation capacity of 3.4 GW) were flooded by the tsunami and required one to two years to fully recover [20]. Renewable energy generation capacity generally performed well. No major damaged was reported on wind farms, and PV capacity outside of the affected region was undamaged but was unavailable due to grid-tied inverters that disconnected during the outage. There was some landslide damage to penstocks and headraces at small hydroelectric power facilities [22].

In February 2011, nuclear power supplied roughly 31% of Japan's electricity. It was considered to be the country's baseload energy and represented 40% of TEPCO's output [23]. The greatest damage inflicted by the earthquake took place at the Fukushima Daiichi Nuclear Power Station. The plant had a total generation capacity of 4.7 GW and consisted of six reactors, three of which were in operation when the earthquake struck [20]. The earthquake caused the loss of the plant's external power supply, and, while the emergency generators started successfully, they were located underground and were flooded by the tsunami [24]. The loss of power lead to core melt in reactors 1, 2, and 3, releasing a massive amount of radioactive material. Within a few days, hydrogen had leaked from the reactor pressure vessels into the building and caused the explosion of reactors 1, 3, and 4 [24].

High voltage transmission lines saw damage from shaking and floating debris and high voltage substations were damaged by shaking [22]. For more than two decades before the disaster, Japanese power utilities had been installing high voltage substations that met seismic qualification guidelines. Quite a number of components at these substations still failed which was likely caused by older, non-qualified equipment encountering higher than assumed ground motions [22].

The tsunami caused some damage to medium voltage substations (66 kV) and extreme damage to the low voltage distribution system [22]. It was noted that an important substation in Hachinohe City stayed intact due to being elevated above tsunami height [20]. Some inland substations suffered short circuits and ground faults from seismic damage. Substations also saw damage to circuit breakers and disconnectors, as well as oil leaking from transformer bushings [20].

Following the earthquake, TEPCO's electrical capacity decreased from 52 million kW to 31 million kW [23]. To combat the power shortage, each electric power company took measures to restore their older fossil fuel-based generation facilities. This lead to thermal power accounting for 90% of ToPo and TEPCO's generating capacity [25]. The disaster also caused the operation of many nuclear power plants to be postponed, dropping nuclear plant operation to 15% by the end of 2011 [25]. To continue meeting customer demand after the earthquake, TEPCO implemented rolling blackouts, allowing groups of two to three million customers to receive power for a three-hour window every 24 hours. TEPCO and ToPo both targeted reductions in customer power use by 15% and achieved this by having large factories shift operation to off-peak hours and installing onsite generation, the commercial sector reducing the use of lighting and air conditioning, and households reducing consumption through any means possible [20].

Japan uses mainly above ground low voltage lines and relatively few buried high voltage or distribution power lines. This design style helped to minimize liquefaction damage to buried power lines [22]. Mobile transformers were an effective measure to quickly restore power to small substations that were damaged [22]. A study by the American Society of Civil Engineers (ASCE) noted that distributed generation resources could reduce the risk associated with extensive power outages after a disaster [21]. The earthquake also showcased the role electric vehicles could play in disasters when 65 Nissan Leafs were made available to local authorities in Sendai to deliver goods and medical supplies while the fuel infrastructure continued to be unavailable [26].

Analysis of the earthquake brought attention to the exceptional performance of microgrids in the aftermath. The Sendai microgrid at the Tohoku Fukushi University in Sendai, shown in figure 5, was developed by NTT Facilities and consists of several distributed energy resources (DERs). Under normal conditions, the microgrid is connected to the ToPo grid and can be disconnected in times of power outage. While the gas engines initially stopped function due to abnormal voltage detection, the PV and battery storage systems remained able to supply critical loads during the outage. The following day, the gas engines were able to be restarted and provided power to important loads until full service was returned [20].

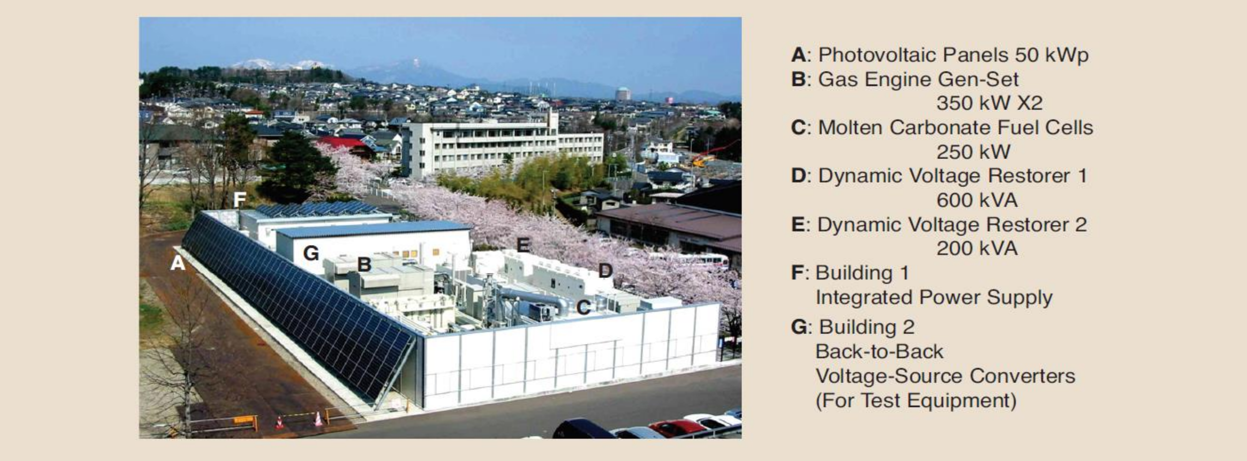


Figure 5 – The Sendai Microgrid at Tohuku Fukushi University [27]

New Zealand 2011 Earthquake

On September 4th, 2010, a 7.1 M earthquake occurred near the Canterbury region of New Zealand. Due to its distance from urban areas, the earthquake only injured approximately 100 people and caused no fatalities. This earthquake initiated an aftershock sequence which lead to a 6.3 M earthquake beneath Christchurch, New Zealand on February 22nd, 2011 [28]. This earthquake was substantially more damaging due to extreme ground shaking, with recorded accelerations of up to 2.2 g, and resulted in 185 fatalities and 7,171 people injured [28]. Although, it was relatively small in magnitude, the position of the epicentre, depth, acceleration experienced, and ground conditions combined to create an extremely devastating event [29]. The repair cost of the earthquake sequence was estimated at around $28 billion US dollars [28].

The earthquake caused significant changes to the environment through liquefaction, lateral spreading near waterways, land level changes, and landslides. Liquefaction caused large amounts of damage to the built environment of Christchurch, with much of the damage experienced by unreinforced masonry buildings [28]. The initial effects on the power grid were primarily due to liquefaction, even though strong ground shaking was observed. Although landslides and rockfalls occurred, they were primarily in regions without dense power infrastructure deployment [30]. It took 10 days to get 90% of the power back on [29]. As electric power is generated south of Christchurch, and was not in the area affected by the Canterbury earthquake sequence, the earthquakes had no impact on power generation [30].

The electric power system in Christchurch is served by Transpower and Orion which operate the country-wide transmission system and local distribution system, respectively [31]. The impacts of both Canterbury earthquakes on the transmission grid were negligible. The Christchurch earthquake caused power to the Christchurch City feeders and substations to be unavailable for 4.5 hours to facilitate safety checks and minor repairs. Following the safety checks, the supply at the grid exit points was restored to full capacity and n-1 security, excluding the Bromley substation which had supply restored to an n security level [31]. The minimal damage to the transmission grid can be credited to the implementation of lessons learned after the 1987 Edgecrumbe earthquake which demonstrated the need to seismically restrain heavier equipment on substations [31]. Transpower's equipment for 220 kV lines were also well installed to IEEE 693 (high zone) standards and were well anchored [30]. Figure 6 illustrates damage from the Christchurch earthquake at various levels of the electrical grid.

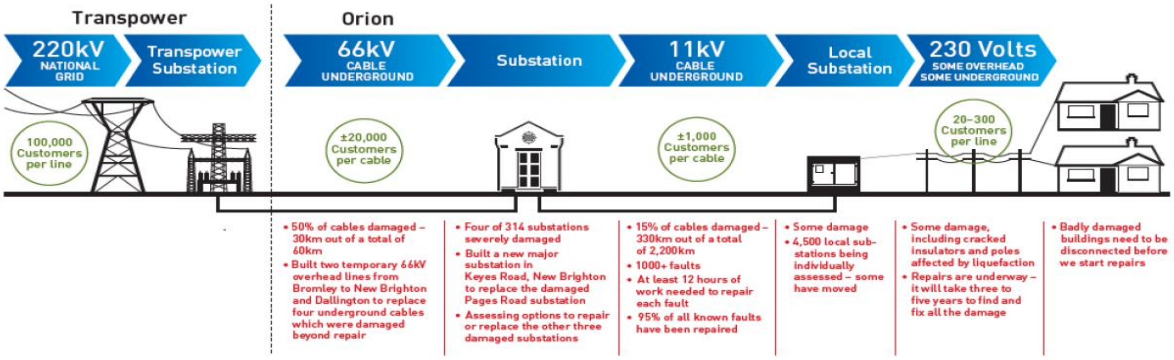


Figure 6 - Christchurch, New Zealand 2011 Earthquake Electrical Grid Damage [29]

While most of Transpower's power lines are overhead, Orion's lines are mostly buried underground. The difference in performance between the transmission and distribution networks can be attributed to buried infrastructure being more vulnerable to the effects of liquefaction [30]. 4 of 314 substations were severely damaged: one due to liquefaction, one from shaking, one from a boulder, and one from its infill wall failing [29]. The lack of damage to the above ground distribution network was credited to work Orion had performed in the previous decade, such as the reinforcement of unreinforced masonry substation buildings [30]. Orion was able to restore power to 50% of households on the day of the event, 75% after two days, 90% within ten days, and 98% after two weeks [31].

Earthquake liquefaction lead to damage of 50% of the 66 kV and 10% of the 11 kV buried cables which lead to widespread power outage [32]. In the 66 kV lines, the cables that were damaged beyond repair were oil-filled. Oil-filled cables in the run from Bromley GXP to the New Brighton and Dallington substations were deemed unrepairable and replaced by temporary 66 kV overhead lines [29]. A total of more than 1,000 faults were identified in the 11 kV cables and occurred in either aluminum or copper core cables [31]. 66 and 11 kV cable failures generally occurred in places that experienced substantial permanent ground displacement (5 cm to 50 cm) [30]. A large amount of the damage occurred in the PILCA (paper-insulated, lead-covered, armoured) 11 kV cables due to existing joints pulling apart.

The successful performance of the New Zealand electrical infrastructure came from a combination of risk planning for likely earthquake events, seismic strengthening of the substations, improvement to key bridge approaches, and improvements in design standards [29]. After the mid-1990s, Orion contributed over $6 million to seismic protection work and a further $35 million to build resilience into their network. It is likely that Orion's $70 million earthquake repair costs would have more than doubled without this work [31]. Following the earthquake, a long-term recommendation was made for Orion and other power utilities to re-assess the seismic weakness of buried power cables. Use of these cables could be mitigated by using overhead transmission and distribution lines through liquefaction zones [30].

Discussion

Lessons Learned from Past Earthquakes

- Available excess generation capacity enables quick recovery
- Electrical grid design with n-1 criteria prevents cascading failure
- The ability to island different portions of the electrical grid increases resilience
- Have available resources to perform grid repairs and plan for aid agreements with surrounding areas
- Where possible, move distribution equipment away from seismically vulnerable buildings, landslide areas, and coastal regions in tsunami zones
- Reinforce unreinforced masonry buildings that contain, or could collapse on, grid components
- If transformers cannot be moved out of tsunami inundation areas, they can be elevated to above flooding height
- Mobile generators and transformers are effective for restoring power
- Telecommunication systems are crucial after an earthquake but can be overwhelmed or unavailable due to lack of power, better to use private forms of communication
- Fuel supply is often scarce following an earthquake
- All three countries had improved grid seismic resilience before the event and were able to restore power to the vast majority of consumers within a week or two
- Utilizing above ground components can prevent liquefaction damage, if buried components must be used, locate them out of liquefaction zones where possible
- There is risk involved in locating generation capacity in tsunami zones or locating too much generation capacity in a single location that could sustain damage – opt instead for a distributed layout
- Rolling blackouts paired with customers reducing demand can be an effective recovery tool if available generation capacity will not meet demand
- Microgrids can remain functional during grid outages and allow power to still be supplied to critical loads
- Electric vehicles can provide mobile energy storage in the aftermath of an earthquake
- Seismic strengthening of existing substations is effective at improving resilience
- Building resilience is less costly than repairing or replacing damaged components after an earthquake

Vancouver Island Electrical Grid

Vancouver Island (VI) is located in the northeastern Pacific Ocean and is part of the Canadian province of British Columbia (BC). The island trends northwest-southeast and is located about 50 km off the southwest coast of mainland BC. VI is separated from the Lower Mainland by the Salish Sea, extends 460 km from northwest to southeast, and is up to 80 km in width [33]. In 2016, VI was home to a population of close to 800,000, with about half of that number living in the metropolitan area of Greater Victoria [34]. Located where the Juan De Fuca plate is subducting beneath the western portion of the North American plate, VI's tectonic environment predisposes the region to earthquakes of the shallow crustal, deeper sub-crustal, and great inter-plate (subduction zone) variety [33].

On VI, BC Hydro runs four hydroelectric systems, with six generating stations and a total capacity of 471 MW. These facilities are supported by transmission infrastructure and additional facilities on the mainland and represent 4% of BC Hydro's total capacity [35]. Figure 7 shows the different hydroelectric systems on VI.

Figure 7 - BC Hydro Vancouver Island Hydroelectric Systems [35]

BC Hydro's generating facilities are only able to meet about 20% of VI's total demand, with about 80% the electricity coming from the mainland through underwater cables [36]. The bulk of VI's power is provided by BC Hydro from the Peace River hydroelectric system through the Kelly Lake substation and from the Columbia River system through the Nicola substation [37]. VI is also home to several independent power producers (IPPs). These include biogas facilities, a wind farm in Cape Scott, run of river hydro projects, a natural gas generation station, and the T'Souke First Nation solar energy project [37].

VI's power grid is connected to the mainland by AC and DC submarine and overhead cables. Two parallel HVAC 525 kV circuits connect the south of Powell River to VI in two submarine and three overhead sections, with a reactor station on Texada Island. There is one 138 kV and one 230 kV AC line that connect Delta to North Cowichan in two submarine and three overhead sections. There are also two HVDC links from Delta to North Cowichan that are considered obsolete and unreliable [38].

Conversations between UVIC and BC Hydro have provided some insight into what damage a Cascadia earthquake event could cause to the VI electrical grid.

BC Hydro expects that damage from a CSZ event could be severe for both the power and natural gas infrastructure (BC Hydro uses a 275 MW natural gas plant in Campbell River which may not renew its electricity production contract in 2022 [39]). Damage to the northern or southern lines connecting with the mainland would lead to outages on the island, and the extent of damage would determine the outage length. The length of the outage could extend anywhere from days to months, depending on the severity of the earthquake. BC Hydro's modelling of CSZ events generally lead to estimates of weeks to months without power and partial restoration following that. After the event, the timeline could extend to years to get back to full functionality. All of the generation plants on the island can run disconnected from the mainland but would not be able to serve the full load. A partial load would be created by temporarily cutting service to industrial customers and by utilizing rolling blackouts (blackout could range from 1 hour on/off to 12 hours or more). It is also likely that load will be reduced due to damage in the distribution system that would lower demand. It was noted that seismic design is not used on system elements past the substations since those portions are commodity designed.

The Peace River and Columbia River hydroelectric systems are located far enough away from the CSZ that they would sustain no damage from the earthquake. It is also likely that the 500 kV transmission system connecting those dams to the Lower Mainland would remain unscathed. BC Hydro is in the process of upgrading dams and water passage systems on VI to align with the necessary seismic standards. If there were to be a major earthquake (over 1 in 1000-year event) before the upgrades are completed, the dams would be at risk of failure. The John Hart dam provides 50% of power generation on the island and has received seismic upgrading. Two upstream upgrades for the John Hart are to be completed by the 2030s, along with a power tunnel replacing the aging penstocks. As it stands, power generation from BC Hydro's VI facilities would not be dependable following a CSZ event.

While the CRD is the most population dense region of VI, it has relatively little nearby generation capacity. The Jordan River Dam is close to Victoria but has the highest seismic hazard of any of VI's dams and is likely to fail in a CSZ event. BC Hydro has also acknowledged that seismically upgrading the dam is not feasible [40]. The Hartland Landfill Project is located within the CRD and generates energy from methane from decomposing waste but would only be capable of producing a fraction of the energy required by the area. Of the nearby AC line connections to Delta, the 138 kV line has the highest risk of failure, and, as of 2021, is not BC Hydro's ten-year plan for replacement. The 230 kV line (installed in 2010/2011) is engineered for a 1 in 2475 earthquake event and would likely weather a CSZ event quite well. There is concern for how much of a power bottleneck would form if the 138 kV line went down and only the 230 kV line was available to bring power to the area. The oil-filled northern crossing lines (found to be bulging and leaking oil in a June 2021 heatwave which resulted in it being temporarily removed from service [41]) from Powell River are only engineered for a 1 in 475 event and are at risk from earthquake damage to their pumping stations. If these lines went down, it is possible that power would have to be directed from the Victoria area to the central and northern reaches of VI. That said, the central and northern regions of VI are closer to the upgraded dam systems and may be able to rely on power from there. There are also elements of the CRD area electrical grid that are located in regions of intermediate tsunami run-up potential of 1-5 m and strong to very strong peak ground accelerations of 0.1 to 0.3 g, shown in figure 8, which could result in substantial damage.

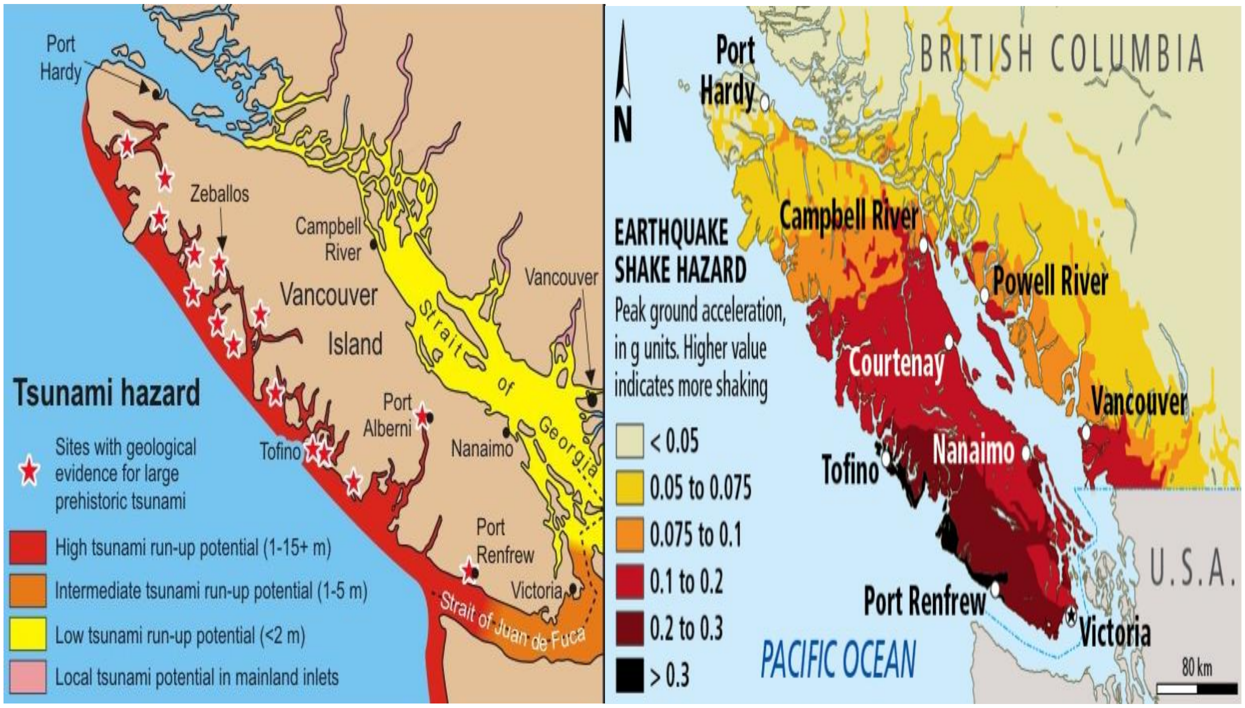


Figure 8 - Tsunami Hazard [42] and PGA for Vancouver Island [43]

Increasing the Resilience of the Electrical Grid

This section will cover actions that can be taken by BC Hydro and the CRD to increase grid resilience and maintain the use of EVs following an earthquake. As it stands, a CSZ event could cause a power outage lasting multiple months on VI. The past earthquakes in Chile, Japan, and New Zealand all had power returned to greater than 90% of customers within two weeks. The actions suggested to BC Hydro are made with the intent of hopefully reducing the outage time from months to weeks. The suggested actions for the CRD are intended to keep their organization able to power their vehicle fleet during an outage and provide power for critical loads.

Suggestions for BC Hydro

More generation capacity should be added to VI which would allow faster recovery in the aftermath of an earthquake. This new generation capacity should be added in a distributed layout, ideally close to the end user, and located outside of tsunami zones. As mentioned above, the CRD contains close to half the population of VI but has little nearby power generation. Adding new generation capacity to the region will mean that it is constructed to modern seismic standards and will able to help meet the increasing electrical load expected from the growing uptake of EVs. If BC Hydro does not want to add more generation to the region, the Province could look at ways to encourage IPPs to create power generation projects in the area.

BC Hydro should ensure that the grid on VI is designed with n-1 criteria and has the ability to island different portions. Where possible, vulnerable system elements should be moved away from seismically unfit buildings (unreinforced masonry buildings, common in Victoria, are a particular concern) and landslide areas. As much of VI has areas of tsunami run up potential ranging from 1 to 15+ meters, grid elements in these areas should be relocated, if possible, or raised to above flooding height. Liquefactions maps can be used to determine where buried system elements cross liquefaction zones and whether they can be relocated above ground. BC Hydro could also focus on seismically reinforcing substations and unreinforced masonry buildings that could damage electrical equipment.

BC Hydro can increase earthquake resiliency by planning for the event. They can plan to have resources available to perform grid repairs and establish agreements with surrounding areas to provide aid following an earthquake. VI should have an available supply of mobile generators and transformers on hand to aid recovery in more remote areas. BC Hydro could also plan for how rolling blackouts can be utilized as power is slowly brought back online and how customers can be compelled to reduce power use if available generation cannot meet demand.

Suggestions for the CRD

Since public communication networks can be brought down due to power outages or from being overwhelmed following an earthquake, the CRD could consider establishing private forms of communication to be able to coordinate their organization in the aftermath of a disaster. Further in this report, an example is provided of a private communication network that could be established with the use of EVs.

The CRD could establish a microgrid to assure that power can still be supplied to charge EVs and power critical loads after an earthquake. The purpose of a microgrid is to generate energy close to the end user. This is different from a more centralized grid, such as operated by BC Hydro, where power is transported long distances from where it is generated to arrive at the end user. Microgrids can be connected to the central grid or operate independently which allows them to continue to provide for customers during a power outage. Microgrids are generally constructed with battery storage and some arrangement of distributed energy resources (solar, wind, combined heat and power, natural gas, fuel cells etc). Currently, BCIT operates a campus microgrid that utilizes wind, solar, and thermal co-gen, along with battery storage, smart grid control systems, and EV charging stations, among other features [44]. In the “EV Use Cases” portion of this report, we’ll look at a Victoria based microgrid that uses a solar array to provide energy for EVs in a post-earthquake scenario.

In net metering programs, a customer who generates electricity is billed for the difference between their electricity use and the electricity that they have provided to the grid. BC Hydro's current policy is to temporarily disconnect net metering customers after a disaster, since they are considered a danger until BC Hydro can conduct site visits. This means that a microgrid that has been established as a net metering customer would not be able to be used after a disaster. To work around this, microgrids can be established "behind the meter", meaning that the power that is generated can be used on site but does not pass through a meter to the larger grid. An organization like the CRD could build a behind-the-meter microgrid that would help to reduce their need for power from BC Hydro under normal circumstances and would allow for EV charging during a disaster. Ideally, a microgrid would allow the CRD to continue charging EVs for an outage lasting a couple of weeks. In the case of an outage lasting multiple months, a microgrid would need substantial attached generation capacity (diesel generators, natural gas turbines etc) to remain a viable source of energy for that entire time period.

Finally, the CRD could utilize the EVs in their fleet as a form of mobile energy storage. Through Vehicle-to-Building (V2B) technology, the CRD can use the battery capacity of their EVs to provide power for important loads. This will be looked at further in the subsequent "EV Use Cases" section.

Vancouver Island Fuel Infrastructure

The information in this section comes from a 2016 University of British Columbia thesis by Allanah Brown that illustrated the fuel transportation system in coastal British Columbia [45].

BC receives crude and refined oil from Alberta, eastern Canada, and Washington State. Fuel arrives in the Lower Mainland by the Trans-Mountain Pipeline (TMPL), marine tankers, rail, and truck. These modes of transport bring fuel to several large storage and distribution facilities in the region. Almost all fuel imports arrive refined, but some crude oil is refined locally at Chevron's Burnaby refinery. A third of BC's transportation fuel is produced at Chevron Burnaby which receives the majority of its crude oil by pipeline, with supplemental deliveries by rail and truck. More than 50% of Vancouver's fuel demand comes via the TMPL and almost 30% of the TMPL's daily oil arrivals are transported from the Westridge Terminal to California, the Gulf Coast, and China. Supplementary fuel supply for the region is imported from Washington State refineries. Marine fuel transport arrives in the Port Metro Vancouver or one of the four petroleum terminals within it. Transportation from distribution centers to end-users is done through trucks, pipelines, storage tanks, and barges. The airport receives its fuel via a 41 km jet fuel pipeline that connects the airport to Chevron Burnaby and the Westridge Marine Terminal.

The majority of fuel that arrives on VI is delivered via the TMPL to the Lower Mainland and then by marine transport to VI. Fuel is transported from the Lower Mainland by barge or marine vessel across the Strait of Georgia to various ports along the East coast of VI. Some ports receive fuel every other week, while others see deliveries as frequently as 2 to 3 times per week. VI has tank farms near Nanaimo, Cobble Hill, and Chemainus which receive fuel through pipelines from nearby marine terminals. After arriving at a port, fuel can be pumped directly into storage where trucks collect and deliver fuel to depots and end-users. Fuel can also be transported in the "roll-on roll-off" fashion, where trucks drop their load on to a departing marine vessel and the load is picked up by another truck after the vessel docks. Additionally, some of the fuel transport on VI is done via rail. The region also receives supplementary fuel from Washington State.

Increasing the Resilience of the Fuel Infrastructure

It bears mention that, as VI gets much of its fuel from the Lower Mainland, VI is directly dependent on how resilient the Lower Mainland fuel infrastructure is.

The Lower Mainland should ensure that the sections of the TMPL that run through potential earthquake damaged areas are built to current seismic standards or are retrofit. TMPL pumping stations should have back up power available to deal with the likely power outage that will follow an earthquake. A study should be conducted to look at locations that receive fuel in the Lower Mainland and how seismically vulnerable they are. Ports in liquefaction areas can improve resiliency through retrofitting or by hardening liquefaction prone soils. The region could also develop an alternate location for a fuel delivery hub that is outside of liquefaction zones [46]. As it is a crucial facility for the region, it should be ensured that the Chevron Burnaby location is seismically robust. Planning should be done with respect to how fuel will be prioritized following an earthquake. There may be temporary measures after an earthquake to stop fuel deliveries to other parts of the world and possibly Vancouver Airport, assuming flights are grounded.

Since VI depends so heavily on ports to receive fuel, it should be a top priority for the region to study how the current port structures are likely to weather an earthquake event. Other than retrofitting existing ports, VI could add additional port locations or capacity, emergency berth structures, alternate landings with roll-on-roll-off capabilities, floating tank farms, and ships equipped with cranes to transfer cargo to land [45]. As VI receives fuel using a “just in time model” that allows 3 days-worth of fuel at any given time, resiliency can be increased by adding additional fuel storage to the region. Planning should be done for how much fuel is expected to be required after an earthquake for vehicle operation and generators. VI should also coordinate planning with the Lower Mainland for how fuel will be prioritized after an earthquake and how much of a decrease in supply from the Lower Mainland could be expected. It may be that regions of the US are less affected by the earthquake and are able to supplement fuel deliveries from the Lower Mainland.

Suggestions for the CRD

The CRD can determine how much liquid fuel the organization would need per day in the aftermath of an earthquake. This would include an assessment of how many gas or diesel vehicles are expected to be operating in that scenario and how much liquid fuel various backup generators would require. Since it is highly likely that ports and road transport networks will be damaged after an earthquake, the Victoria area may be cut off from fuel shipments for some time. As VI only has about a three day supply of fuel at any given time, the CRD could establish a private storage of fuel for the organization.

It is worth noting that hydrogen vehicle fuel would have the same resilience issues as gas and diesel with respect to how it would be transported to VI after an earthquake. The CRD would be need to stockpile enough hydrogen fuel locally to continue the use of hydrogen vehicles after a disaster. An idea to increase hydrogen resilience would be to add local production of it to VI. There is potential to reform hydrogen through thermal, electrolytic, solar-driven, and biological processes [47]. Production of hydrogen via electrolysis using BC's clean energy would also have very low carbon intensity [48].

The CRD can also consider what the resilience implications are of their fleet composition. Adoption of EVs will allow the organization to reduce GHG emissions, lower costs for fuel and maintenance, and potentially donate energy in a disaster. That said, if there is a prolonged power outage, and there is no local energy generation, the EV fleet would become effectively useless after their batteries had been drained. There is also the question of charging availability. If fast charging is unavailable, it could take up to 8 hours to charge an EV at a conventional charger which would be 8 hours that the vehicle would be unable to provide disaster relief for. ICE vehicles would still contribute to the organization's GHG emissions but would have beneficial features in a disaster, such as further travel distance on a full tank and very short times to refuel. ICE vehicles are also dependent on fuel that could be unable to make it to VI following an earthquake. Hydrogen vehicles don't create GHG emissions (assuming hydrogen fuel has been refined from clean energy) and offer quick refueling times but rely on hydrogen that may be unavailable after an earthquake. An idea for optimal fleet resilience would be for the CRD to maintain a fleet of several different vehicle types, along with trying to mitigate vehicle risk by methods such as using microgrids and creating storage of conventional fuel and hydrogen.

EV Use Cases after an Earthquake

EV Communication Network

As mentioned previously, public forms of communication are frequently overwhelmed in the aftermath of an earthquake. Communication networks are important for disaster recovery as they allow the delivery of crucial information to help the preservation of life. Mobile ad hoc networks (MANETs) offer the ability to connect a group of wireless mobile nodes without the use of existing network infrastructure or centralized administration. These wireless nodes can form a temporary network dynamically which makes them well suited for disaster recovery and search and rescue efforts [49].

A vehicular ad-hoc network (VANET) is a variety of MANET where vehicles act as mobile nodes. In the past, VANETs have often been constructed with gasoline powered vehicles. A benefit of using an EV in a VANET is that an EV can operate as a communication node for a long period of time whether it is moving or stationary, due to the large capacity battery of an EV [50]. It has also been proposed that unmanned aerial vehicles (UAVs) could be used in conjunction with EVs to help guide rescue efforts, due to their ability to monitor terrain from an elevated perspective [51].

Researchers at the University of Malaga studied the energy consumption of a VANET composed of 40 vehicles and covering an area of 120,000 m^2. In a 180 s scenario, each vehicle consumed roughly 4,000 J of energy [52]. This would only represent 0.0018% of a Nissan Leaf Plus's 62 kWh battery capacity.

EV Donating Power with V2B

Another application of EVs is the use of them as mobile energy storage. With its onboard battery, an EV can charge at a station, drive to another location, and donate its power via V2B (vehicle-to-building) technology. Until recently, EVs had only been capable of one-way charging. Bidirectional charging allows vehicles to discharge battery power into a building or the electrical grid. Currently, the Nissan Leaf and the Mitsubishi Outlander are the only vehicles capable of this on the Canadian market [53]. For the purpose of this example, we'll assume that the CRD is using the Nissan Leaf Plus, shown in figure 9, with a 62 kWh battery capacity.

Figure 9 - 2022 Nissan Leaf Plus [54]

The example for this use case takes place after an earthquake in July. There is a complete power outage, and the CRD is providing a Nissan Leaf Plus to donate its power to a shelter for people displaced in the earthquake. The Nissan Leaf Plus will have access to a 50 kW fast charger that can charge the battery to full in about 60 minutes [55]. The fast charger is located on a community microgrid that is still able to provide power during the outage. The shelter that the EV will donate power to is located 10 km away from the charging station, and the Nissan Leaf Plus uses roughly 2 kWh/10 km [56]. We will assume that the Nissan Leaf Plus will discharge a power of 50 kW to the shelter for about one hour, an energy donation of 50 kWh. For reference, the average Canadian household uses about 19 kWh per day [57]. In this example, the total energy use for the EV to provide this function is 54 kWh (50 kWh for energy donation, 4 kWh for travel). We will also assume that the time required to drive the round trip distance of 20 km in a post-earthquake damaged transport network, along with the time to hook the EV up at either the shelter or the charging station, will take a total of one hour. The process would look as follows:

1. EV starts at fully charged state
2. EV drives 10 km to shelter and hooks up V2B discharging (about 30 mins)
3. EV donates 50 kW of power for one hour
4. EV drives 10 km to fast charging station and hooks up to charger (about 30 mins)
5. EV is charged fully at fast charging station in one hour

All told, the process would take around 3 hours, and each 3 hour cycle would donate another 50 kWh to the shelter while using 54 kWh of energy at the fast charging station. It is worth noting that discharging this deeply, fast charging, and charging the battery to 100% capacity would increase battery degradation, but it is assumed that post-disaster circumstances have necessitated using the EV in this fashion. If the vehicle provides disaster relief for a full 24 hours (assuming employees working in shifts), the EV could repeat this cycle 8 separate times, donating 400 kWh to the shelter and using 432 kWh at the fast charging station.

The microgrid that the vehicle returns to is assumed to have a 100 kW (standard size for a commercial rooftop) solar array available. Using the System Advisor Model (SAM) software provided by the National Renewable Energy Lab (NREL), a simulation was performed for a 100 kW roof-mounted solar array in Victoria, BC with a fixed tilt angle. Figure 10 shows what the monthly energy production would look like for the proposed array.

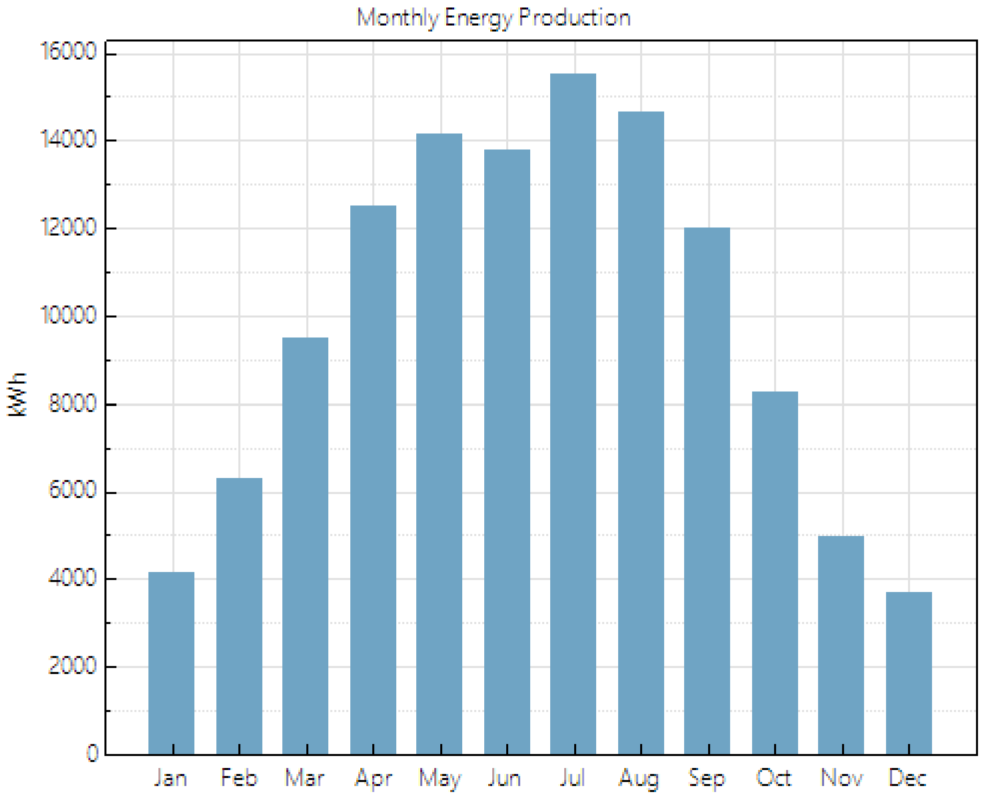


Figure 10 - Monthly Energy Production of a 100 kW Fixed Tilt Solar Array in Victoria, BC

Looking at the energy generation for the month of July, the array would produce about 15,500 kWh. Averaging this number over the 31 days of the month leads to an average daily energy production of 500 kWh. This means that the 24 hour EV use case of 432 kWh, described above, would use almost the total daily energy production of the array. It bears mention that this is also for an earthquake occurring in a month with the most available solar energy. The solar array would only produce about 122 kWh of energy in an average December day which would only accommodate 2 of the energy donation cycles described previously. If multiple EVs were wanted to provide this same functionality, the microgrid would have to have substantial battery storage, along with alternative forms of attached energy generation, such as diesel generators or natural gas turbines. A green solution to this problem could be to use renewable natural gas synthesized from the Hartland Landfill.

EV Providing Transport for Goods and People

A final application of EVs in a post-earthquake setting is the transport of important goods, such as food and medical supplies, along with people. In this context, people could be skilled employees to perform a certain task or those in medical need. It may be the case that certain CRD duties, such as ones relating to water and waste, continue to be crucial in the aftermath of a disaster.

For this case, we will once again consider the 62 kWh Nissan Leaf Plus. Nissan lists the Leaf Plus's maximum single charge range as 363 km [55]. While it's hard to predict what sort of driving distances would occur when providing earthquake relief, it is likely that an EV that is providing 24 hour disaster relief would only need to charge once or twice a day with that amount of vehicle range.

Assuming that the vehicle is close to completely discharged after use, it would take about 60 kWh to charge the vehicle completely. If a vehicle providing disaster relief is only charged once a day, the 500 kWh solar energy production, described in the previous July earthquake scenario, would be able to provide for 8 separate vehicles acting in this fashion. In comparison with the previous EV use case, you would be looking at a single vehicle that performs 8 power donation cycles over a 24 hour period vs 8 separate vehicles that are transporting supplies or people over the same period of time.

Conclusions

EVs offer many benefits when compared to ICE vehicles, such as reduced GHG emissions, better performance, and economic savings. EVs sales have continued to grow, even during the pandemic, and could represent 12-28% of the global fleet by 2040. The CRD has one of the largest concentrations of EVs in the province, and this will only continue to grow as the Zero Emissions Vehicles Act takes effect in 2040. The CRD also coincides with the region of BC that would be hugely impact by a CSZ earthquake event. To maintain the use of EVs in an earthquake, it is integral that the power system infrastructure is resilient.

To understand how to improve earthquake resilience, this report examined past earthquakes in Chile, Japan, and New Zealand. The 2010 Chile showed the importance of having available excess generation capacity, designing the grid with n-1 security criteria, establishing private forms of communication, and utilizing smaller sized generators for recovery in isolated areas. The 2011 Japan earthquake illustrated the risks of locating generation capacity in a tsunami zone and taught lessons on the importance of elevating transformers in flood zones, utilizing rolling blackouts for recovery, and the resilience of microgrids after an earthquake. The 2011 New Zealand earthquake taught lessons on the potential damage that can be caused to electrical equipment running through liquefaction zones, along with how impactful spending money on resilience upgrades can be. All three earthquakes had power returned to most customers within two weeks, and this success can be at least somewhat attributed to the robust seismic standards that had been put into place in all three countries.

The electrical grid on VI was examined and ideas for increasing resilience were applied to the region. The grid on VI depends heavily on imported power from the mainland of BC. BC Hydro's earthquake modelling suggest that the region could experience power outages in the range of months after a CSZ event. BC Hydro could increase resilience by adding more generation to the area, specifically near to the CRD, where there is little nearby generation capacity. BC Hydro could also relocated grid elements from tsunami zones, reinforce substations and masonry buildings, move buried system elements from liquefaction zones, and plan for the event by having resources available and arranging for aid agreements with surrounding areas. The CRD could increase organizational resilience by establishing private forms of communication, building a local microgrid to be able to charge EVs in a disaster, and utilizing their EV fleet battery capacity to provide mobile storage and provide power to important loads.

The fuel infrastructure on VI was also examined, including its connections to the Lower Mainland. VI depends heavily on fuel that arrives in the Lower Mainland from the TMPL and is then brought to VI by marine transport. Improvement to the Lower Mainland fuel resilience, such as hardening liquefaction prone soils in ports, providing backup power for pumping stations, and deciding fuel prioritization will all help to ensure there is a supply of Lower Mainland fuel available for VI. VI can also improve its resilience by adding additional ports or emergency berth structures, increasing fuel storage, and planning for how fuel will be prioritized and where it can be sourced from. As an organization, the CRD can plan for what their expected fuel needs will be after an earthquake for vehicles and generators and establish how much storage that would require.

Post earthquakes use cases were examined for EVs. EVs have the potential to act as nodes in a mobile communication networks. In a 180 s simulation, the power need for this application was found to only represent 0.018% of a Nissan Leaf Plus's 62 kWh battery. In a scenario with an EV donating power to a shelter and charging at a 50 kW fast charger, it was found that an EV could donate about 400 kWh to a shelter in a given 24 hour period. It was assumed that the EV was recharging at a microgrid with a 100 kW solar array which was able to provide power for a single vehicle acting in this fashion. Finally, the case of an EV delivering supplies and personnel was observed, and it was found that, given the Leaf's single charge range of 363 km, 8 vehicles could charge once a day at the 100 kW solar microgrid and provide this function for 24 hours.

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